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Spacecraft Environments Interactions: Space Radiation and Its Effects on Electronic Systems

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PREFACE

The effects of the natural space environment on spacecraft design, development, and operation are the topic of a series of NASA Reference Publications* currently being developed by the Electromagnetics and Aerospace Environments Branch, Systems Analysis and Integration Laboratory, Marshall Space Flight Center. The objective of this series is to increase the understanding of natural space environments (neutral thermosphere, thermal, plasma, meteoroid and orbital debris, solar, ionizing radiation, geomagnetic and gravitational fields) and their effects on spacecraft, thereby enabling program management to more effectively minimize program risks and costs, optimize design quality, and achieve mission objectives.

This primer, eighth in the series, outlines the radiation environments encountered in space, discusses regions and types of radiation, applies the information to effects these environments have on electronic systems, and addresses design guidelines and system reliability.

See NASA RP 1350 for an overview of eight natural space environments (including space radiation) and their effects on spacecraft.

* NASA Reference Publications Natural Space Environments Series, available from the Marshall Space Flight Center Electromagnetics and Aerospace Environments Branch, include the following:

"The Natural Space Environment: Effects on Spacecraft," James, B.F., Norton, O.A., Jr., and Alexander, M.B., November 1994, NASA RP 1350.

"Spacecraft Environments Interactions: Protecting Against the Effects of Spacecraft Charging," Herr, J.L. and McCollum, M.B., November 1994, NASA RP 1354.

"Electronic Systems Failures and Anomalies Attributed to Electromagnetic Interference," Leach, R.D. and Alexander, M.B., July 1995, NASA RP 1374.

"Failures and Anomalies Attributed to Spacecraft Charging," Leach, R.D. and Alexander, M.B., August 1995, NASA RP 1375.

"Spacecraft Systems Failures and Anomalies Attributed to the Natural Space Environment," Bedingfield, K.L., Leach, R.D., and Alexander, M.B., August 1996, NASA RP 1390.

"Spacecraft Environments Interactions: Solar Activity and Effects on Spacecraft," Vaughan, W.W., Niehuss, K.O., and Alexander, M.B., November 1996, NASA RP 1396.

"Meteoroids and Orbital Debris: Effects on Spacecraft," Belk, C.A., et al, August 1997, NASA RP 1408.

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ACRONYMS AND ABBREVIATIONS

AT&T	American Telephone & Telegraph
CCD	Charge Coupled Device
cm	centimeter
CMOS	Complementary Metal Oxide Semiconductor
EDAC	Error Detection And Correction
eV	electron volt
GCR	Galactic Cosmic Radiation
ISC	short circuit current
keV	kiloelectron volt
km	kilometer
krad	kilorad
LET	Linear Energy Transfer
mg	milligram
mil	distance equal to 1/1000 of an inch.
MeV	Megaelectron volt
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
PMAX	maximum power
rad–hard	radiation hardened
SAA	South Atlantic Anomaly
SEB	Single Event Burnout
SEE	Single Event Effects
SEGR	Single Event Gate Rupture
SEIDC	Single Event Induced Dark Current
SEL	Single Event Latchup
SEMBE	Single Event Multiple Bit Error
SEFI	Single Event Functional Interrupt
SET	Single Event Transient
SEU	Single Event Upset
TDE	Total Dose Exposure
TID	Total Ionizing Dose
VOC	open circuit voltage

SPACECRAFT ENVIRONMENTS INTERACTIONS: SPACE RADIATION AND ITS EFFECTS ON ELECTRONIC SYSTEMS

INTRODUCTION

In the last 25 years the National Geophysical Data Center recorded over 4500 spacecraft anomalies or malfunctions that have been traced to the effects of the space radiation environment.[1] These occurrences range from solar array to attitude control problems. While glitches in the power supplies or upsets in the data downlink may be considered minor effects, a loss of attitude control is a catastrophic, possibly mission–ending, effect.

With the advent of the "smaller, better, cheaper, faster" philosophy, spacecraft systems increasingly use modern microelectronics manufactured by commercial processes. Modern microelectronics continually decrease feature size and increase component density. These practices and other requirements for advanced technologies, increase radiation sensitivity. Utilization of commercial technology adds more risk through the use of electronics that are not "hardened" to the radiation environment.

Major complaints about working with radiation–hardened electronics are cost and availability. The cost to harden a satellite to the natural space radiation environment by using rad–hard electronics is typically about one percent of the total system cost.[1] With possible mission–ending effects, this seems a trivial argument. In addition, the cost comparisons made do not always include all hidden costs. When using commercial technology, pre-existing radiation test data cannot be used. Enough lot-to-lot variation occurs in these parts to consider them different parts. Therefore, every lot of commercial parts procured for a mission with radiation requirements must have radiation testing. This process is time consuming and expensive. For a fair comparison, these costs must be included in any cost analysis.

The availability argument, however, is becoming closer to reality. While the original argument was that all types of parts were not available, now fewer manufacturers are willing to produce radiation–hardened electronics. In the last five years Texas Instruments, Intel, TRW, LSI Logic, and AT&T exited the radiation–hardened microelectronics market.[1] What this means for the spacecraft system designers is that designing for the radiation environment will become increasingly difficult if this exodus continues. It also means a heightened awareness to the radiation environment and its effects on electronic systems is needed. Hence, this primer provides a broad overview of the natural space radiation environment and its effects on spacecraft systems.

SPACE RADIATION ENVIRONMENT

Sources

The same types of radiation exist throughout the entire region of space in our known solar system. The quantities and spectrum of these radiation types vary with location in the solar system. This primer deals only with the near–Earth radiation environment (i.e., the environment experienced by Earth orbiting spacecraft). This section introduces the source of radiation in the near–Earth regions and the following section discusses these in detail.

The near–Earth radiation environment can be divided into a trapped radiation environment and transient radiation environments. A depiction of these environments is shown in Figure 1. The trapped environment is due to the Earth's magnetic field confining charged particles to certain regions of space. These regions are termed the "Van Allen Belts." Nominally there will be one proton and two electron belts (inner and outer), though this can temporarily change with large solar events. The transient environments are due to the effects of the Sun (solar wind and flares) and galactic cosmic radiation (GCR). A two–dimensional artist's depiction is shown in Figure 2 and a three–dimensional model–based view of these trapped belts is shown in Figure 3.[2]

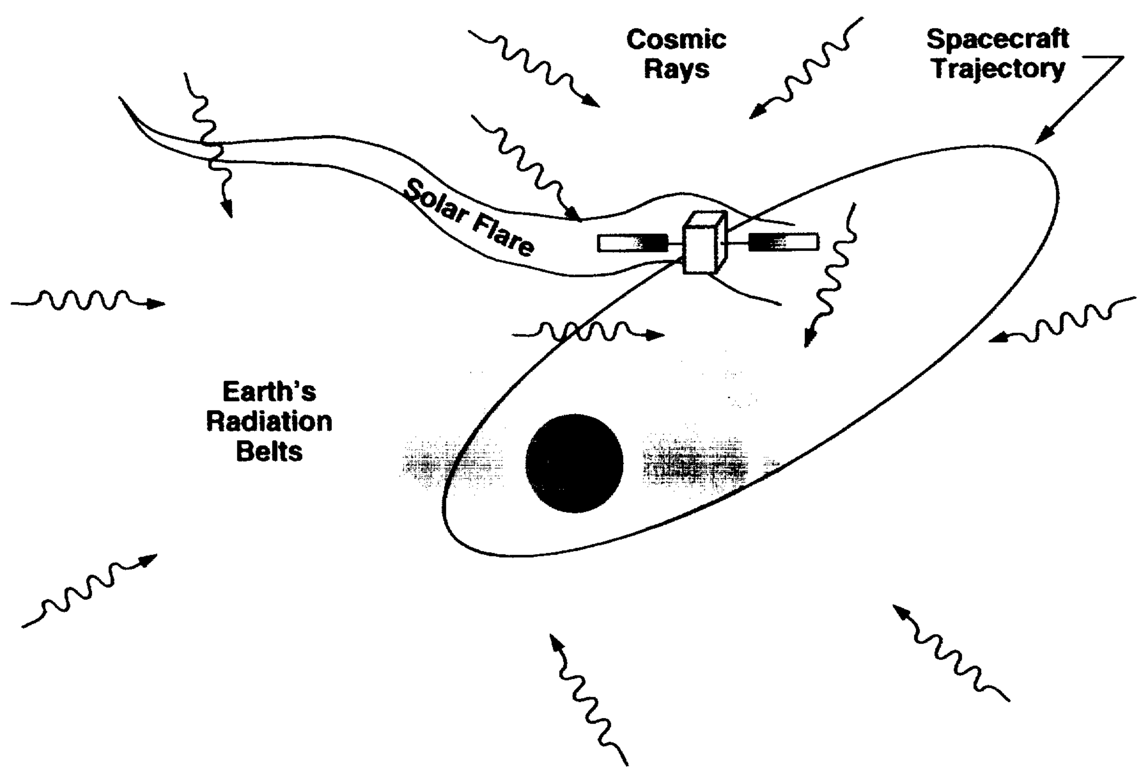

Figure 1. Cartoon depicting all the radiation types that a spacecraft can experience, including the inner and outer trapped radiation belts, solar flares, and galactic cosmic radiation

The transient radiation environments, consisting of solar wind, solar flares, and galactic cosmic radiation, exist in the interplanetary space regions as well as the near–Earth regions. The solar wind consists of low energy electrons and protons and is typically only energetically significant for externally mounted spacecraft components. This wind is generally ignored because it is insignificant compared with other radiation sources.

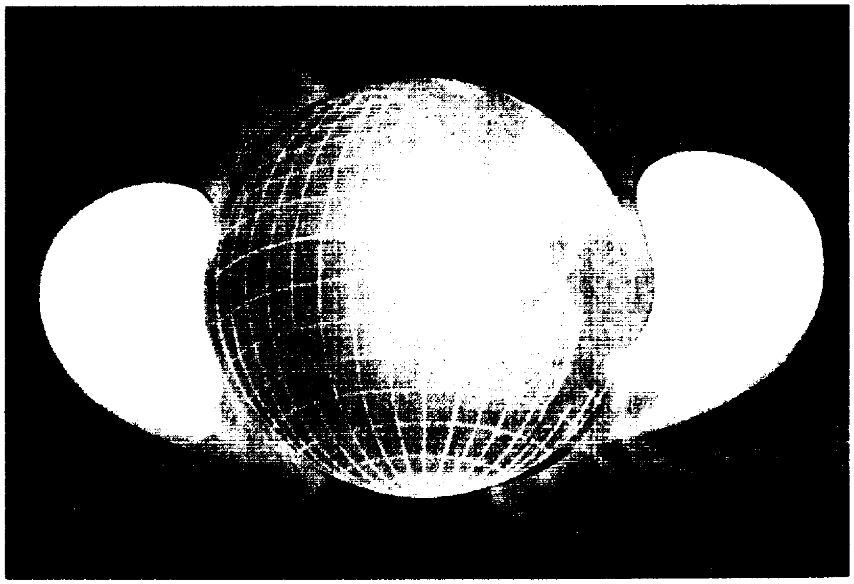

Figure 2. Two–dimensional artist's depiction of the trapped radiation environment[3]

The other solar–induced radiation environment is solar "flares" (The general term flare is used for convenience to represent all types of solar radiation events). When a magnetic disruption in the solar photosphere occurs, a variety of radiation types and energies erupt from the Sun into space. This flare can produce energetic protons and heavy ions that will produce effects in electronics (described in the next section). An important influence on solar particle radiation (and all transient environments) is the Earth's magnetic field. The magnetic forces that cause charged particles to be trapped, also act on charged particles in flares. For a given magnetic field strength, an incident particle energy is required to penetrate that magnetic field. All lower energy particles are deflected along the magnetic field lines. This magnetic screening can be significant for satellites in low–Earth orbit.

The third source of radiation is galactic cosmic radiation. GCR is electrons, protons, and heavy ions (charged particles with atomic number greater than one) that are believed to have an origin outside the solar system and to be omnidirectional. As with the solar flare environment, this radiation source is significant in the near-Earth environment. The GCR is affected in the same manner as solar particles due to the effects of the Earth's magnetic field (i.e., low altitude equatorial orbits will receive significant screening, while higher inclination or altitude receive less).

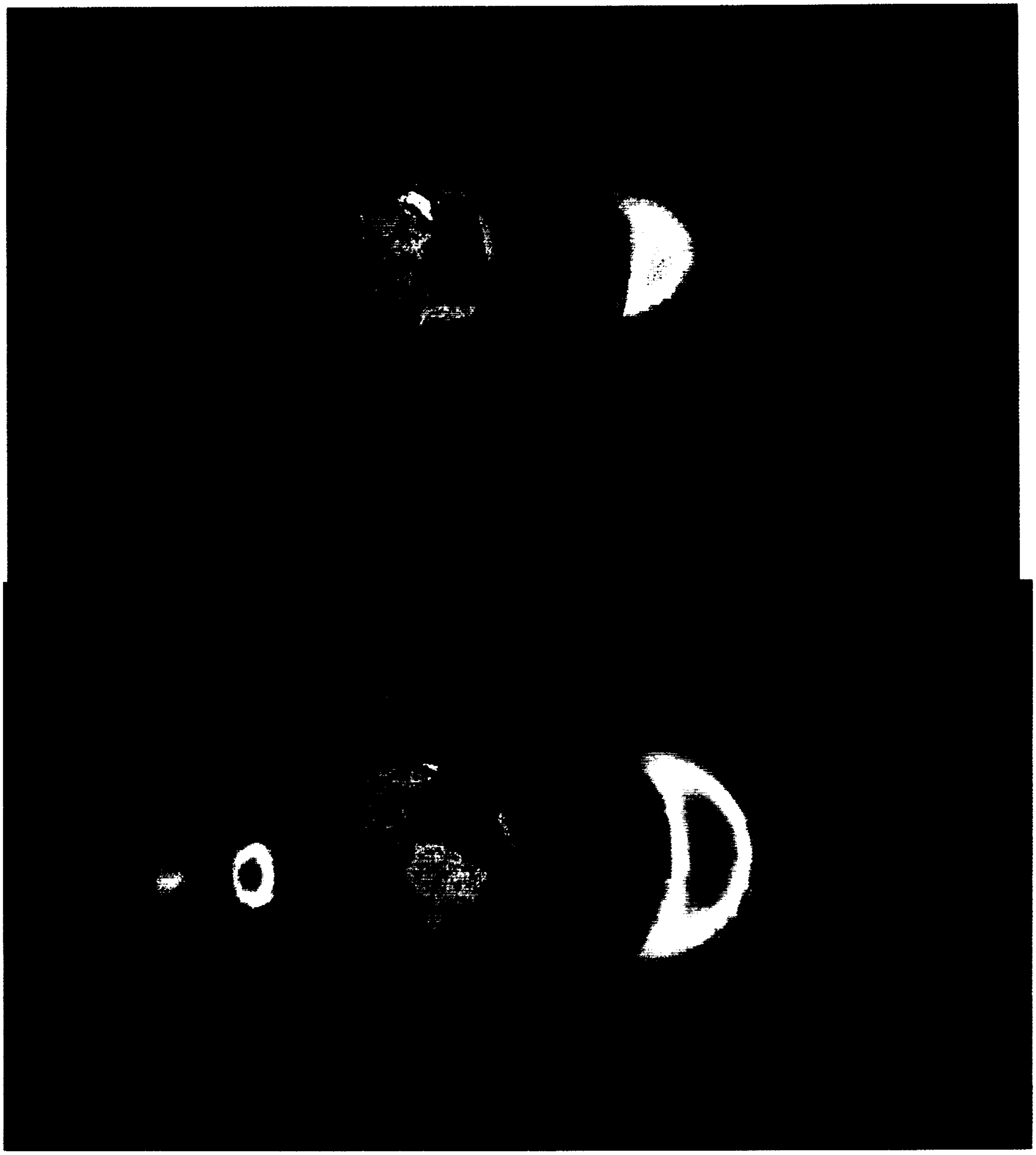

Figure 3. Three–dimensional views of the trapped radiation environment. Top view shows the true toroidal shape of the radiation belts, with transparent green representing the outer electron belt and solid green the proton belts (data from a particularly strong storm event where a second proton belt was formed). Bottom, edge–on view shows cross–sectional data for the belt regions with low to high density represented by blue to red.

Near–Earth Radiation Environment

Trapped Environment

Figure 4 shows the approximate regions of space the various radiation environments occupy. Since boundaries of the bands are not sharp transitions, the indicated numbers should be considered approximations. The trapped radiation belts extend from approximately 500 km to about 12 Earth radii (roughly 76,000 km). Normally, over this range there are two electron bands (with different population and energy spectra) and one proton band. As shown in Figure 3, however, sometimes a departure from normalcy occurs. Figure 3 is based on data from a severe solar event, lasting for many weeks, in 1989 that formed a third electron belt (between the inner and outer zones) and a second proton belt (higher in altitude).

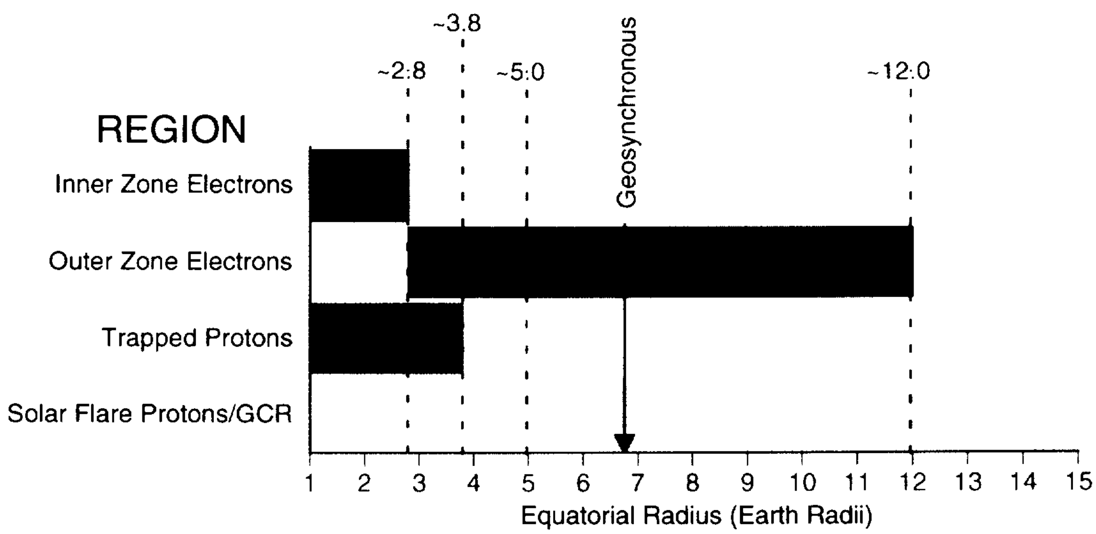

Figure 4. Pictogram showing regions of space where radiation types are significant.[4] Regions are plotted as a function of the equatorial radius, in Earth radii (~6370 km), because the belts vary with the magnetic field that changes with increasing inclination off the equator.

A specific region of space that warrants special coverage is the South Atlantic Anomaly (SAA). The Earth's magnetic field axis does not point to geographic north and does not pass directly through the center of the Earth. The combination causes a deformation of the magnetic field over the South Atlantic (magnetic field lines dip lower in altitude) and over Southeast Asia (field lines are higher in altitude). The net effect is the harshness of the radiation belts is seen at lower altitudes in the SAA region (Figure 5). Thus, for spacecraft in low–Earth orbit, this region tends to dominate the observed radiation environment. For systems at higher altitudes, however, this effect is less significant.

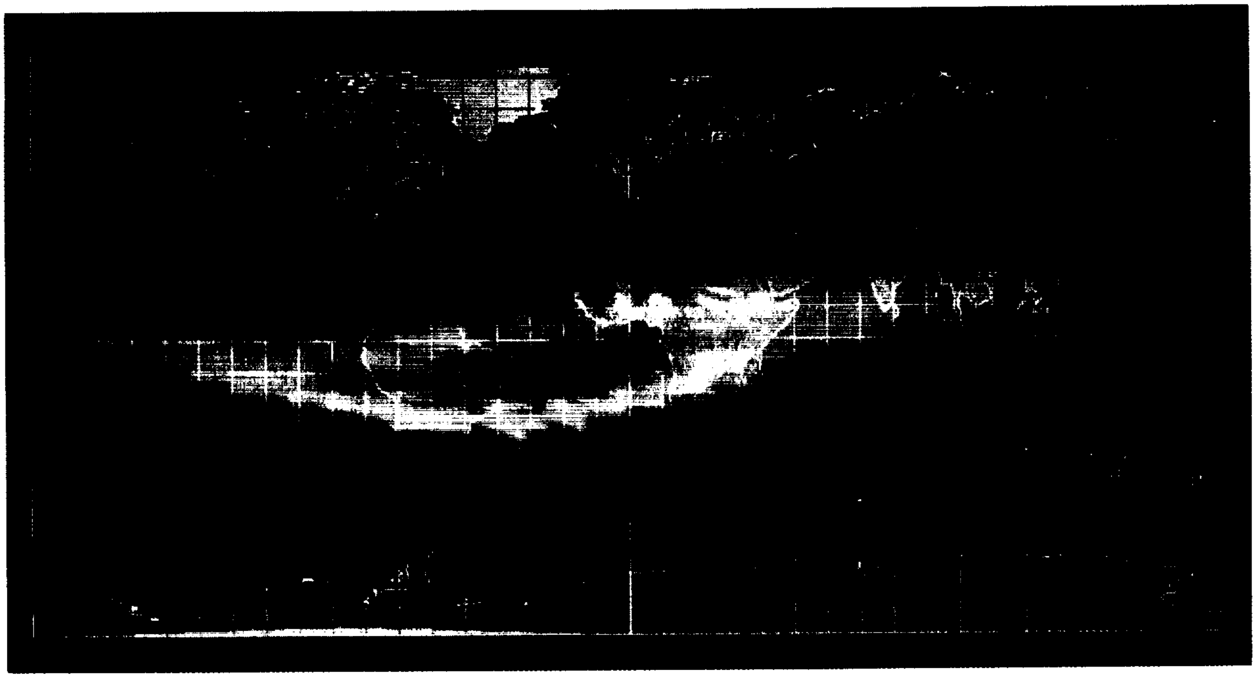

Figure 5. Contour plot of the trapped proton environment overlaying a map of the Earth.[2] Proton density increases from blue to green to yellow to red. Contours highlight the South Atlantic Anomaly (SAA) where the radiation particle population is high due to the offset nature of the Earth's magnetic field.

Another important point is the orbit of a spacecraft can take it into and out of the radiation belts. Figure 6 shows the electron environment as a function of time for a satellite in low–Earth polar orbit. It is evident there are times of radiation exposure followed by times of no exposure.

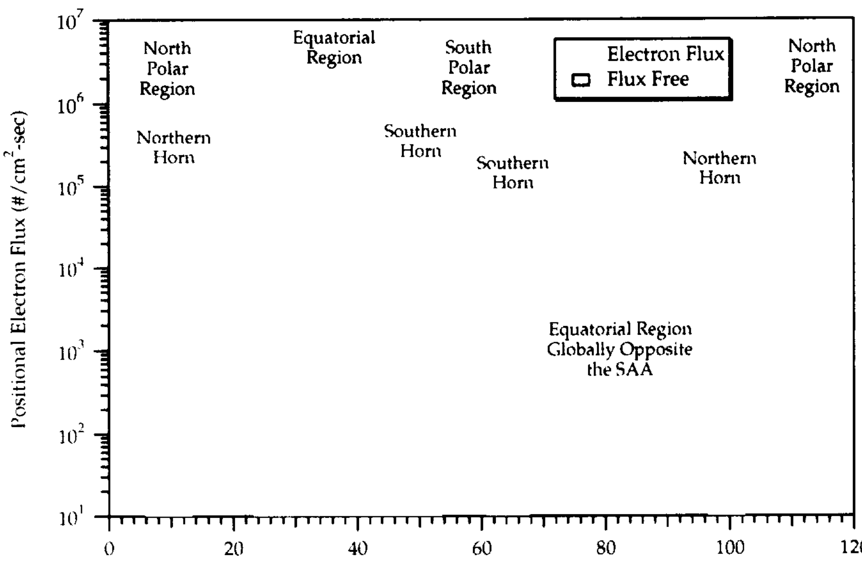

Figure 6. Plot of trapped electron flux as a function of relative orbital time for a 900–km polar orbit.[4] The graph shows the regions of the radiation belts and the noncontinuous exposure. Note: horn identifies regions of space (at high latitudes) where the outer electron belt is seen at lower altitudes.

Net effect of this orbital variation of the radiation environment is the build–up of total ionizing dose (TID) occurs at different rates (giving a fine structure to a dose versus time curve, shown in Figure 7) and the single event effects (SEE) susceptibility is only for a certain portion of the orbit (both of these are discussed in detail in the Effects of Radiation section). Understanding this orbital variation is important to properly predict the environment, design ground–based tests, and accurately predict the rate effects.

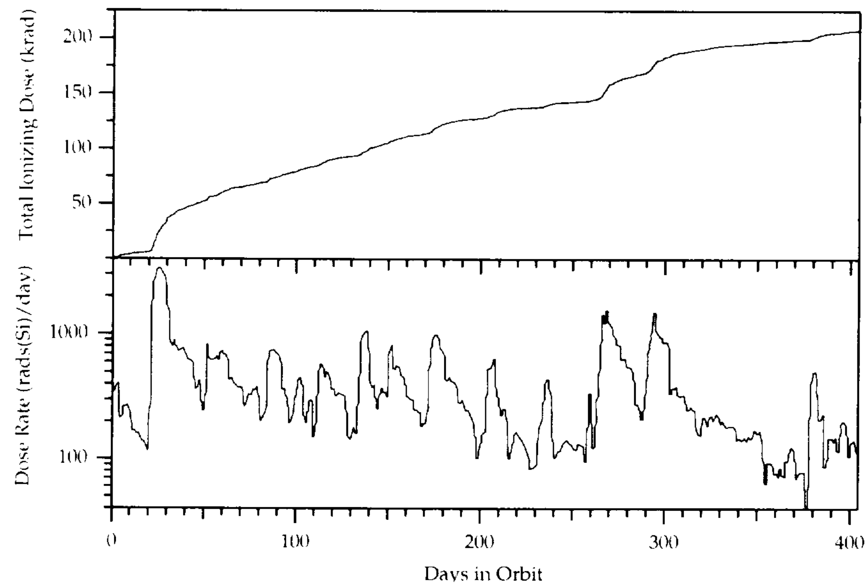

Figure 7. Plot of daily dose rate and total ionizing dose (TID) as a function of days in orbit. Visible are the effects of flux free time in the dose rate curve. For long term averages the TID curve shows an average dose rate value (not a bad assumption) but jumps exist when the dose is viewed locally in time.

Transient Environments

The previous section discussed the sources and nature of the transient environments. The issue here is their impact in the near–Earth regions. In Figure 4, the bar representing the solar flare protons depicts the upper end of the environment extending throughout space, whereas, the lower end shows the point where geomagnetic effects are beginning to remove some of the environment. Since this removal is a strong function of particle energy, altitude, and inclination, depicting how the gray bar extends down in altitude is problematic. Detailed computer calculations are required to predict this geomagnetic cutoff effect. Because this same region of space and geomagnetic effects are associated with galactic cosmic radiation, this bar is used to represent GCR as well.

Summary

This section briefly outlined the radiation environments encountered in space. The discussion included regions and types of radiation, as well as special considerations such as orbital variations and the South Atlantic Anomaly. The following section applies some of this information to the effects these radiation environments have on electronic systems.

EFFECTS OF RADIATION

Radiation Interactions

To understand the effect radiation in space has on electronics systems, one must first understand the radiation environment and how it interacts in electronic materials. The natural space radiation environment was addressed first in this primer. To do an overview of the effects of radiation on electronic systems, the only information needed from that section is the environment consists of electrons, protons, and heavy ions. Making predictions, discussed in the next section, requires using detailed knowledge of particle types, energy spectra, and density.

Figure 8 shows a diagram of the radiation environment and its effects on electronic systems. The flow is from the radiation environment (top) to interactions that take place (middle) to effects that these interactions lead to (bottom). Observe first the inclusion of photons in the electron box. While high energy photons do not represent a significant portion of a natural space environment, the interaction of the electrons in surrounding spacecraft materials can produce a locally significant photon population. Since the photon interactions in electronic materials produce only high energy electrons which are indistinguishable from the natural environment electrons, their interactions and effects are included in the natural electron environment.

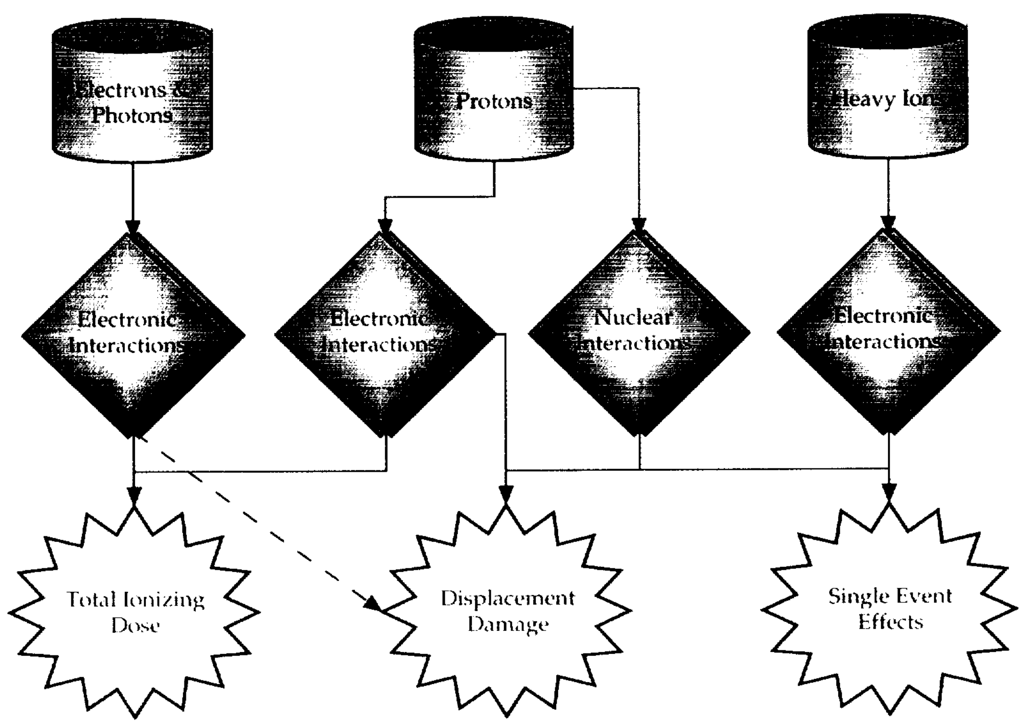

Figure 8. Diagram of radiation environment effects on electronic systems

The middle section of Figure 8 shows two interactions. While four boxes are shown, electronic and nuclear are the only interactions. In electronic interactions, the incident radiation interacts with the surrounding charge of the atom (i.e., the electrons). The effect of this type interaction is to transfer energy from the radiation to the atom. The newly acquired energy raises the energy state of the atom to a higher level and causes an excitation or ionization of electrons within the atom. For electronic materials, an increased number of electrons (and associated positive ion) become available for conduction or other effects within the crystalline structure of the semiconductor. If sufficient energy is transferred, the atom can become so thermally stimulated it leaves its lattice site. In general, this is a small percentage interaction that requires a significant electron flux to produce noticeable effects (hence, a dashed line to the displacement damage box). Heavy ion electronic interactions, however, deposit a significant amount of energy. Therefore, along with the link to the single event effects which depend on the transient charge generated, a direct link is made between the heavy ion electronic interactions and the displacement damage box.

For the nuclear interaction to take place, radiation must interact directly with the nucleus of the atom. Here the incident radiation must overcome the electronic reaction with both the electrons and the nucleus so that it approaches the nucleus sufficiently close so direct nuclear interaction is possible. While all radiation types show paths through an electronic interaction box, only the protons have a path through the nuclear interaction box. Only protons, with their unitary charge and high energies, interact with any reasonable probability with the nucleus. Once the nuclear interaction begins there are many ways the atom can display the effects. So much energy is transferred in this type interaction, it is easy to have the atom physically displaced from its original location or even, in effect, explode, fragmenting the nucleus into smaller pieces. Nuclear interactions have a more dramatic impact but the probability of occurrence is much lower than the electronic type of interaction.

The bottom layer of Figure 8 shows three effect categories: total ionizing dose, displacement damage, and single event effects. A discussion follows of each category with an outline of the basic effects. Examples of how the spacecraft environment produces these effects and possible mitigation techniques are given.

Effects of Radiation on Electronics

Total Ionizing Dose (TID)

The term, total ionizing dose, implies the dose is deposited to the electronics through ionization effects only. From the above discussion, energy deposited by radiation moves the electrons to a higher energy state, thus making them available for conduction and mobile inside a nonconductive material. These electrons, or more correctly the positive charge created by ionization, are the prime cause of the total ionizing dose effects.

In general, all types of electronics are susceptible to ionization but the charge generated inside the semiconductor material can quickly be collected and removed without ill effect (assuming the radiation interaction rate is at the low level of the space environment). If a semiconductor device contains, for example, a silicon dioxide/silicon interface (as in all modern integrated circuits based on complementary metal oxide semiconductor (CMOS) technology), charge generated inside the oxide can become trapped at the interface. This trapped charge, by changing the potential of the interface structure, can lead to increased "leakage" current or changed operational characteristics of any device using this structure (if this interface exists at a biasing point).

From an engineering perspective, these macroscopic effects are important in determining the reliability of electronics to the ionizing dose environment. To determine a part's reliability in this radiation environment, a detailed set of test data is required. Simply testing a part for functionality after exposure to a given radiation level may not be sufficient. Parametric data must be taken with functionality testing over smaller dose steps than one-shot, go/no-go testing. Test data for all parts in a given design must be reviewed for meeting all specifications (not just functionality). Table 1 shows typical data from a TID test: the part's parameters, data sheet specifications, and the effects on those parameters as a function of the total dose exposure (TDE), and annealing steps. The word anneal, here, is a misnomer. No improvement is implied; it is simply a temperature over time treatment without the influence of the radiation environment. This data shows the parameters Icc_ttl, Icch_cmos, and PSSR_A no longer meet manufacturer's specification at completion of the testing. This information must be combined next with aging and temperature effects. Finally, overall degradation must be compared with actual circuit specification to ensure proper operation throughout mission lifetime.

Test data must also show information useful for mission procured electronics. A high degree of variability in test results is possible for the same parts from the same lot from the same manufacturer. The data presented in Table 1 are for one part and only shows 10 electrical parameters and their results. Actually this part had 53 parameters tested for each of the cited conditions. Actual testing should include a number of parts from the same lot and the data should be treated statistically based on observed variability and sample size. Variability results from the attention paid by the manufacturer to designing and building parts while being mindful of the radiation environment. A manufacturer producing a "rad-hard" part will have a small amount of variability. A mass produced part for the commercial market, however, can have extreme variations. Therefore, testing should be tailored for the radiation quality of the commercial part (i.e., from accepting previous test data for rad-hard parts to performing piece-part testing). As more and more manufacturers leave the radiation tolerant market, testing of parts becomes more critical to system design.

Table 1. Example of electrical test data from a TID qualification test

	Electrical		Spec Limit			TDE	TDE	Anneal	TDE	Anneal
#	Parameters	Units	Min	Max	Initial	1 krad	2 krad	48 hr @ 28 °C	3 krad	168 hr @ 100°
1	Icc_ttl	mA	0	2	0.8	2.9	7.6	7.0	6.2	6.4
2	Icch_cmos	mA	0	0.4	0.2	3.1	5.7	4.5	5.7	5.9
3	Iih_CLK	μA	-1	1	-0.3	0	0	-0.3	-0.1	-0.2
4	Iil_CLK	μA	-1	1	-0.2	-0.2	-0.1	-0.1	-0.2	-0.2
5	Iih_CLR	μA	-1	1	0.1	0	-0.1	-0.2	-0.1	-0.2
6	Iil_CLR	μA	-1	1	-0.4	-0.4	-0.3	-0.2	-0.2	-0.2
7	PSSR_A	%	0.001	0.001	0	0	-0.002	-0.001	-0.003	-0.003
8	GSFE_A	lsb	-0.5	0.5	0	0	0	0	0	0
9	IE_A	lsb	-0.5	0.5	0.1	0.2	0	-0.3	-0.2	-0.2
10	DNL_A	lsb	-1	1	0.2	0.1	0.5	0.2	0.5	0.5

In general, TID effects are mitigated through proper use of shielding materials. These effects depend on transfer of energy from the radiation environment. If the particle environment population or its energy is decreased, the effect is lessened, i.e., exactly what shielding does. By forcing the particle to transport through an intervening material, the environment interacts and loses energy (sufficient energy loss can mean the particle never enters the electronics). By appropriately selecting the shielding material and its thickness, mitigation is optimized. Since nothing is free, the cost associated with shielding is weight. Putting weight into orbit costs money. Therefore, the tradeoff is survivability or reliability of electronic systems versus added cost to get systems into space. Also, the effect of shielding is not linear. At some point, depending on the environment and relative "hardness" of the electronics, addition of reasonable shielding is no longer effective. The only reliable mitigation is replacement of the part with a more tolerant version. This point will be demonstrated in the final section.

Displacement Effects

The second area of the cumulative effects of radiation is displacement effects. When radiation interacts with the material, either electronically or via direct nuclear interaction, energy is imparted to the atom as a whole. This energy is typically seen as heat by the increasing vibrational motion of the atoms. Or if sufficiently high, the energy supplied to the atom can overcome the binding energy of the atom in the crystalline lattice of the material. If this occurs, the atom is "displaced" from its normal position to various end locations. Unless the end location is an exact duplicate of the former position, the regular order of the crystalline lattice is disturbed.

This regular order gives semiconductor materials their unique properties. The disturbance causes changes in the operation of any device exposed to this environment (level of dose a device is susceptible to varies, but all electronics are affected). This change may add a current path that previously did not exist (allowing increased leakage current) or make conduction more difficult in regions designed for flow. For example, diodes become less effective (two-way current flow becomes easier) and the inherent amplification capabilities of transistors diminish. Similar to the total ionizing dose, effects of displacement damage are cumulative. With small exposure to a radiation environment observable effects are small but effects build with exposure time.

The solar cell is an example for this category since it displays these described effects and is a common element to most spacecraft. The solar cell is basically a diode with one side exposed to the illumination of the Sun. Simply put, photons hit the device, creating electrons. The electric field of the diode (cell) allows the electrons to be collected, thus, generating power. To repeat, with exposure to radiation, diodes become less effective. Diode leakage current increases, generated electrons "live" for much shorter time periods, and the internal electric field decreases. All these effects combine to make the solar cell less efficient producing power. Power reductions of 50 percent are possible depending on solar cell construction and the environment to which the cell is exposed. In general, shielding is effective for mitigating displacement effects, but adding shielding to resolve this solar array problem is difficult. The shielding (called cover glass in this application) must be transparent to the optical photons and make a good optical interface at the solar cell (minimize refractive effects). Even with these conditions met, transmission losses increase with increasing cover glass thickness. Therefore, a balance must be reached between allowable radiation degradation and cell power production efficiency.

Single Event Effects (SEE)

Single event effects (SEE) are effects in microelectronics induced by the passage of a single particle through the part. This is the area where high energy protons (both from trapped environment and solar flares) and galactic cosmic radiation are important. It is interesting to note the first prediction of GCR effects on microelectronics came in 1962 in a paper by Wallmark and Marcus.[5] They stated the ultimate scalability (how small devices can be made) of electronics would be limited by the direct ionization effects of GCR. While not correct in the scalability limit, they did correctly predict single event effects over 10 years prior to any observation of the effect.

SEE is a generic term encompassing all possible effects. Over the 20 years that effects of single particles have been investigated, many acronyms were devised to indicate the effects caused by these single particles. The most common of these are single event upset (SEU) and single event latchup (SEL). Acronym practice attaches to SE a letter or letters that indicate the effect. With the wide range of effects and associated acronyms, it is accepted in the radiation effects community to refer to SEE, then draw the distinction between destructive and nondestructive events. Examples of events defined (and observed) to date are shown in Table 2.

Table 2. Listing of Single Event Effects Acronyms

SEU	Upset	Digital circuit changes logic state
SEL	Latchup	Device switches to a destructive, high current state
SEGR	Gate Rupture	Destructive failure of a power transistor
SEB	Burnout	Another mode of destructive failure for a power transistor
SEFI	Functional Interrupt	Device enters mode where it is no longer performing the designed function
SEMBE	Multiple Bit Error	More than one logic state change from one ion
SET	Transient	Transient current in circuit
SEIDC	Induce Dark Current	Increased dark current in CCD arrays

From a systems engineer's point of view, exactly how upsets occur is less important than how to accurately predict the rate these events occur. Since all single event physics is not completely understood, the only recourse to achieve a rate prediction is to perform experiments on a part–by–part basis. Experiments at a special facility count and correlate every ion and event in the electronics. The result is cross section versus energy data for protons and cross section versus linear energy transfer (LET) for heavy ions. LET is a parameter that indicates how a particle loses energy as it passes through a material. Cross section is an indication of the susceptibility of a part to the event (a large number implies more susceptible, a small number, less). Cross section is used because the units are area units (cm^2). The abscissa of these experiments (energy for protons and LET for heavy ions) is based on an important parameter for the event to occur. Since protons have a direct nuclear interaction, no directional/depth dependence exists so the particle's energy is used. For heavy ions that can dramatically change energy and LET over the sensitive region of a part, a strong directional/depth dependency does exist. Therefore, a parameter must be used that can deal with this dependency. LET is such a parameter.

To get to a rate prediction for the mission, the part–by–part experimental information must be appropriately merged with the environmental data predicted. Not only must this be done on a part–by–part basis but also on an effect–by–effect basis. If a part is susceptible to both upset and latchup, experiments must measure the cross section of both effects and predict a rate for each. Typical units used for rate prediction are events per bit–day or events per device–day. The word events is replaced with upsets, latchups, etc., as appropriate. Use of per bit or per device is arbitrary. To convert from per bit to per device, multiply by the number of bits susceptible to that type single event effect in the device.

Unlike TID and displacement effects, single event effects gain little help from shielding. Unless a part is extremely susceptible to low energy or low LET single event effects (indicates a very high rate of events), adding shielding does not significantly degrade the environment producing the effects. A general rule of thumb is SEE cannot be shielded against. The main option to reduce these effects is parts selection. If parts selection is not an option (e.g., no other available part with the functionality), circuit level mitigation techniques are used. Examples are error detection and correction (EDAC) circuitry and voting. A simple EDAC example is using a checksum bit. Each row in a memory array has an additional bit that stores a 1 or 0 if the sum of the other bits is odd or even, respectively. If a bit in that row is upset, the new checksum does not agree with the stored checksum bit, hence, an error.

On a mission critical system or a system where EDAC may not be effective, multiple numbers of parts of concern are operated concurrently. The voting method takes advantage of the low rate at which SEE occur, i.e., the extremely rare probability of more than one part upsetting in exactly the same way and producing the same type output error within a short period of time. If an odd number of concurrent parts is employed, a vote is taken of the output of the parts and majority rule is observed. This method is very effective detecting errors but must be weighed against the increased cost and complexity required.

This section discussed three categories of radiation effects, gave examples, and briefly outlined mitigation options. Using knowledge of these effects and the radiation environments an electronic system can be exposed to in space, a comprehensive set of design guidelines should be implemented. These guidelines need not indicate only the environment, but also the environmental effects. The uncertainty in these should be shown through the proper use of engineering design margins. Only through strict adherence to design guidelines and margins can system reliability be properly considered. The next section addresses the design guidelines and reliability issues.

DESIGN GUIDELINES AND RADIATION ENVIRONMENT PREDICTIONS

To enhance electronic system reliability in the space radiation environment, specific design guidelines that address the effects described in the previous section should be implemented. An integral part of design guidelines is the environment predictions for the electronics design engineer. Typically, a project report that includes the explicit particle environment and a processed version of this information is generated for the design engineer. An example is shown in Figure 9.

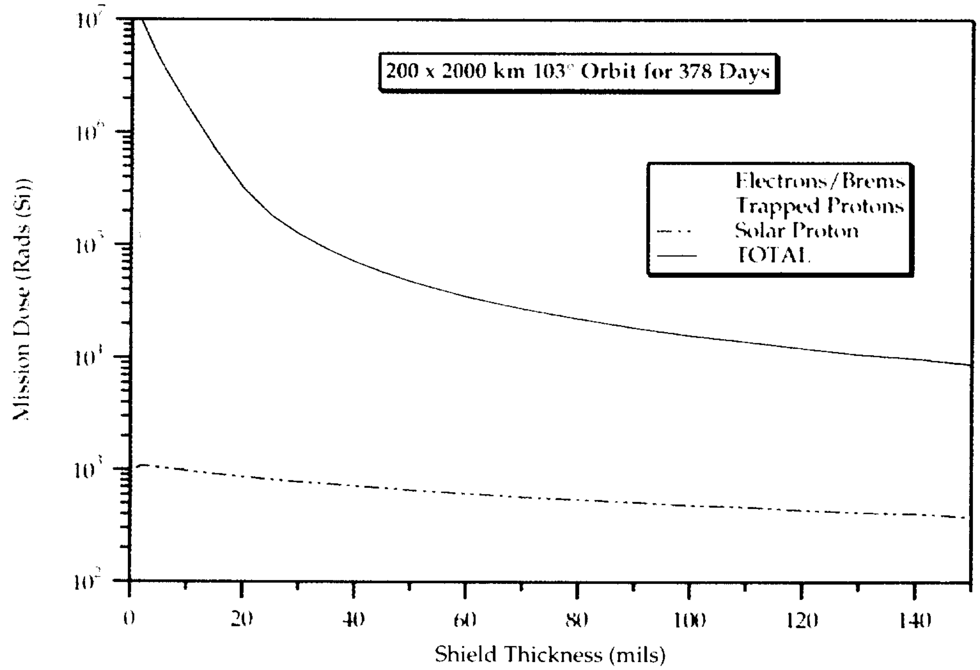

Figure 9. Plot of mission dose as a function of 4π aluminum spherical shield thickness. Dose axis may be either a mission dose (this case) or an annual dose for long duration missions.

To a first order approximation the electronics container (system box and spacecraft) is considered a spherical aluminum ball with the electronic part at the center. To use Figure 9, assume an average thickness (box wall thickness plus the spacecraft skin thickness) for a given system and estimate the mission dose the system parts receive. For example, assuming a 120–mil average thickness, the expected mission dose is approximately 12 krads. If all electronics in this box can be shown to maintain reliability at this level of radiation with some design margin (typically a factor of 2 to 10, assuming a margin of two, gives 24 krads in this example), then the system analysis is complete. If not, more detailed dose analysis is needed, additional radiation shielding required, or the affected parts replaced with more radiation tolerant versions.

The decision to go to a more tolerant part is often based on the effectiveness of additional shielding. From Figure 9, approximately 60 mils of additional shielding decreases the dose at the 80–mil point by a factor of two (approximately 20 to 10 krads). On the other hand, about 8 mils of additional shielding reduces the dose at the 20–mil point by the same factor of two (approximately 320 to 160 krads). At higher initial shield thickness, this difference becomes even more apparent as the dose-depth curve (Figure 9) continues to flatten. Therefore, it becomes less cost effective (in weight) to add shielding to reduce dose to electronics if much shielding is already present.

The second area to consider in environment prediction is displacement effects. It was once assumed that on a typical mission the only items particularly sensitive to the displacement environment are solar cells. Recent studies show that other devices such as precision voltage references and optocouplers have enhanced degradation from displacement effects. Therefore, if the expected mission environment includes a significant displacement damage environment, then suspect parts must be tested and evaluated for these effects. Which parts are suspects and how vulnerable they are is an active area of research.

Solar cells, however, have been studied extensively for these effects. Continuing with solar cells as the example, the normal environment prediction document includes this effect in a table indicating the effective 1 MeV electron flux for a variety of solar cell materials and cover glass thickness (Table 3).

Table 3. Example of solar cell displacement effects predictions. All values are in units of 1 MeV equivalent electron flux per year.

Silica Cover Glass (mils)	*Silicon*			*Gallium Arsenide*		
	PMAX	*VOC*	*ISC*	*PMAX*	*VOC*	*ISC*
6	4.20E14	4.20E14	1.60E14	1.54E14	2.16E14	7.71E13
8	2.64E14	2.64E14	9.88E13	1.06E14	1.49E14	5.34E13
12	6.40E13	6.40E13	2.64E13	1.99E13	2.78E13	9.82E12

The values presented in Table 3 are used by the solar cell design team to evaluate how various solar cells perform in flight in the specified radiation environment. These generic values are based strictly on the environment for the orbit of interest and typical solar cell materials. By coupling these values with radiation test data (typically supplied by the manufacturer), the solar cell design team can predict the electrical performance of solar cells at mission end.

The final example of radiation environment prediction, often the most difficult, is the single event effects. Figure 10 shows the environment prediction for SEE environment during solar minimum conditions. During an active solar period when solar flares can occur, a second curve is typically added to indicate possible conditions in that extreme environment. As pointed out in the previous section, to accurately predict the rate at which the single event effects occur, electronics testing is required. This test data must be combined with the environment data (presented in Figure 10) to determine the actual rate at which these effects occur. Since the effects prediction rate inherently relies on the test data for the specific electronic part, this type prediction is not possible until parts are identified. Thus, designs must be an interative process. Preliminary designs are completed first, then evaluated for

SEE. This evaluation returns to the designer with recommendations for part replacement and/or circuit modifications. This iterative process continues until both designer and radiation engineer are satisfied with the design. If not done in this manner, a dilemma can arise when a part is identified as a problem but the design is too far along to change the part or system design.

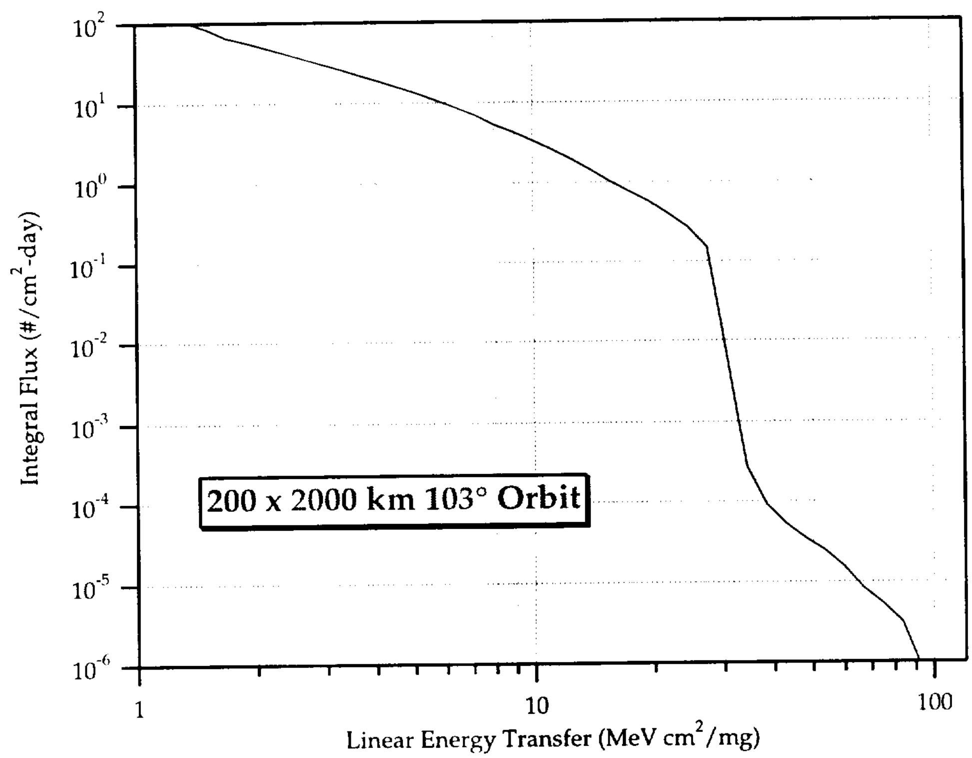

Figure 10. Single event effects (SEE) producing environment for a polar orbit. An important feature is the rapid reduction in the environment for LET greater than approximately 28.

There are methods to alleviate SEE problems. The first divides all the spacecraft systems into three categories such as vital, mission important, and non-critical. Once systems are categorized, intelligent parts procurement of appropriate level of radiation hardness is possible.

Vital systems include areas of life support, attitude control, etc. These systems cannot tolerate any effects (i.e., one upset may jeopardize mission safety or cause complete mission failure) and must use radiation hardened electronics.

Mission important systems, if affected, would substantially impact probability of mission success. Effects on these systems have a significant impact on mission operations but are recoverable. A mixture of rad–hard and nonrad–hard technologies is appropriate. The mixture is based on a rate prediction at preliminary design through mission operations.

Finally, non-critical systems, if affected, would be able to tolerate the errors without significant degradation or the effects can be removed through post-processing (typically data systems). Data may be taken at a rate of many per second while effects may occur a few per day. Comparisons of sequential data points would allow extraction of good data from bad. These systems can accept a significant fraction of commercial technology as long as detailed reliability analyses and rate predictions are performed.

The second method to alleviate SEE problems is to have a design guideline that specifically restricts catastrophic failures. A number of single event effects discussed in the last section can produce catastrophic failures (e.g., latchup, burnout, etc.). Having designs that are current limited (latch-up tolerant) or operated at reduced voltages (burnout resistant) prevents these failures. Of course, the most effective method is to use parts not susceptible to these failure mechanisms.

The third method includes a review of parts selection as early as possible in the design process. This method's importance is not restricted to single event effects. Since all radiation effects discussed require experimental verification of radiation tolerance, very early identification of parts that require testing (compared to those with existing test data) is vital. SEE testing takes significant time because it must be done at a specialized facility with restricted availability. Identification of a part and early replacement impact design and completion time the least.

CONCLUSIONS

This primer provides a brief survey of space radiation environments and their effects on spacecraft electronics systems. Discussions of total ionizing dose and displacement damage show electronics have a cumulative damage mode that continually increases over the lifetime of the spacecraft. The single event effects discussion shows the radiation environment can impact a mission from the very beginning and, without precaution, can cause catastrophic failure. From the discussion of possible mitigation techniques, it is apparent that consideration of these environments early in the design process is a necessity.

The early involvement of radiation specialists in mission planning, system design, and design review (part–by–part verification) is a must. During the mission planning phase environment prediction gives an early indication of problems the mission may encounter. Additionally, orbit optimization minimizes the impact of the radiation environment on mission goals.

Equally important is early involvement by these specialists in initial system designs. Improvements in circuit designs can be easily incorporated to mitigate certain radiation effects. Also, electronic box designs can be optimized. Intelligent placement of susceptible electronic components takes advantage of existing shielding (hiding a TID sensitive part behind a large transformer). Placing local spot shields minimizes the size and weight required to achieve required shielding. Systems are optimized with respect to radiation effects and weight by such prudent placements.

In the design review, a part–by–part verification ensures all electronics meet program design guidelines and specifications. While this task may seem formidable initially, if mission planning and system design are accomplished, the work should proceed with no surprises. Granted the space radiation environment does presents design concerns but they can be addressed and systems designed to withstand them.

Questions or comments should be directed to the MSFC Electromagnetics and Aerospace Environments Branch, Steven D. Pearson, 256-544-2350.

GLOSSARY

annealing	The process associated with the change in electrical or material characteristics, induced by radiation, due to the effects of time and temperature. The normal connotation is an improvement in the characteristics, but in the case of total ionizing dose, this is not always the case.
burnout	A catastrophic failure of a high power transistor caused by transient radiation. In the space environment a single ion can induce a degenerative feedback current in the transistor that will lead to its failure due to excessive current.
dark current	The leakage current associated with the cells of a CCD array. A high level of this background current tends to make the image turn dark.
diode	A two terminal electronic device that allows current flow in only one direction. Applying voltage of one polarity induces a current whose level is exponentially related to the voltage. Applying voltage of the opposite polarity allows no current flow in the forward direction, but allows a very small reverse current called leakage current.
displacement damage	The damage that occurs to a material, which has a well–ordered crystalline lattice structure, that is disturbed by radiation displacing some of the lattice elements.
dose	The energy absorbed per unit mass from any radiation in any material. This indicates the amount of energy transferred to the material through which the radiation is passing. The most common unit is the rad, which is the deposition of 100 ergs per gram of material. The SI unit, however, is the Gray (Gy), which is 1 J/kg or 100 rad.
electron	The fundamental atomic building block particle with a net charge of negative one.
electron volt	The kinetic energy an electron gains by its acceleration though a potential difference of one volt.
energy	When used in the radiation effects area, the energy refers to the kinetic energy the particle has, which is directly related to the square of the velocity of the particle. Typical unit used is MeV.
fluence	The number of particles passing through a given area. The fluence is the time integrated flux. Typical unit is cm^{-2}.

flux	The number of particles passing through a given area per unit time. Typical units are cm^{-2}-sec^{-1}.
gate rupture	A catastrophic failure of a high power transistor caused by transient radiation. In the space environment a single ion can induce sufficient charge buildup and discharge occurs across the gate of the transistor. A short circuit develops and the transistor fails.
heavy ion	The atomic nucleus of an element greater than hydrogen with a number of electrons less than the electrically neutral atom. The difference between the number of electrons present and the number in the neutral state is called the charge state of the heavy ion.
horns	The region of the outer electron belt that, due to the bending of the Earth's magnetic field at the higher latitudes, exists at low altitudes. These regions can be a significant source of dose for spacecraft in low–Earth orbit with high inclinations.
latchup	A destructive, high current mode of operation that CMOS structures can transfer into if the parasitic structures exist and the radiation induced transient currents are sufficiently high. If not current limited, due to the current feedback and temperature effects, the current will continue to increase until the part fails from overcurrent.
LET	The linear energy transfer is that amount of energy an incident particle will transfer, locally, to a given material per unit distance. Typical units are MeV-cm^2/mg.
mil	A distance unit equal to 1/1000 of an inch.
photons	A radiation type that is electromagnetic energy that quantum mechanically interacts as both a wave packet and particle.
proton	The fundamental nuclear building block particle with a net charge of positive one. A proton is also the nucleus of a hydrogen atom.
rad	Unit of absorbed dose equal to 100 ergs/gm.
rad–hard	Terminology that indicates the electronic component design was modified to ensure radiation reliability and survivability. This category is sometimes divided into military and space qualifications, where the military qualification also indicates a nuclear weapon survivability specification.
rad–tolerant	Terminology that indicates the electronic component design was not modified to ensure radiation reliability and

survivability but has a significant level of tolerance to radiation inherently in its design.

SEE	A single event effect is an effect in an electronic device that is induced by the passage of a single ionizing particle through its structure. The effects can vary from simple bit flips to catastrophic failures.
TID	The total ionizing dose is the cumulative buildup of dose that produces effects in electronics by ionization of the materials in the device.
upset	The most common form of single event effect. In digital microelectronics, information is stored as a zero or one. An upset is the transition from one to the other (i.e., zero to one or one to zero).
Van Allen Belts	The region of space where the Earth's magnetic field has "trapped" radiation. Due to the dipole nature of the Earth's magnetic field and the intensity variation with altitude, any charged particle that enters into this region will continually travel along the lines of force, effectively "trapping" the particle.

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The natural space environment is characterized by complex and subtle phenomena hostile to spacecraft. Effects of these phenomena impact spacecraft design, development, and operation. Space systems become increasingly susceptible to the space environment as use of composite materials and smaller, faster electronics increases. This trend makes an understanding of space radiation and its effects on electronic systems essential to accomplish overall mission objectives, especially in the current climate of smaller/better/cheaper faster.

This primer outlines the radiation environments encountered in space, discusses regions and types of radiation, applies the information to effects that these environments have on electronic systems, addresses design guidelines and system reliability, and stresses the importance of early involvement of radiation specialists in mission planning, system design, and design review (part-by-part verification).

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